

Physics at Super B

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Abstract. Flavour will play a crucial role in understanding physics beyond the Standard Model. Progress in developing a future programme to investigate this central area of particle physics has recently passed a milestone, with the completion of the conceptual design report for Super B , a very high luminosity, asymmetric e^+e^- collider. This article summarizes the important role of Super B in understanding new physics in the LHC era.

The major challenge facing particle physics in the next decade is to go beyond the Standard Model (SM) of elementary particles. Historically, progress in the field has been achieved through advances on two parallel approaches – the energy frontier and the luminosity frontier. While the LHC will soon deliver the much anticipated leap forwards in available centre-of-mass energy, a comparable advance from the current world record luminosities achieved by the B factories will allow complementary research into new physics (NP).¹ This is a simple consequence of the fact that quantum physics allows for the virtual production of heavy particles, which influence processes at energies much below their masses. Therefore, to investigate NP through quantum effects, high precision, rather than high energy, is required.

The flavour sector is well-suited to search for quantum effects of NP since flavour changing neutral currents, neutral meson-antimeson mixing and CP violation all occur at the loop level in the SM, with quark flavour violation further suppressed by the small mixing angles. Since there is no *a priori* reason for NP to share these features, the quark sector is potentially subject to large NP effects. Similar arguments apply in the lepton sector, where the theoretical interest is even greater, since the physics behind neutrino oscillations remains an open question.

Many observables in the flavour sector are generically sensitive to NP effects, including rates and asymmetries of rare leptonic or loop-induced K , D and B decays, mixing and CP violating phenomena in the K^0 , D^0 , B_d^0 and B_s^0 systems, electric and magnetic dipole moments of charged leptons and lepton flavour violating μ and τ decays. While certain models focus attention onto particular channels, there is no single “golden mode” – rather, the flavour sector can be thought of as a treasure chest of NP-sensitive observables. Indeed, the plethora of measurements that can be made adds significantly to the physics programme, enhancing the sensitivity to NP. Moreover, correlations between observables can distinguish between different NP models.

A coherent programme for particle physics research in the next decade should therefore allow as many flavour observables as possible to be studied. No single experimental facility can cover them all. However, a “Super Flavour Factory”, *i.e.* a high luminosity, asymmetric e^+e^- collider has a very wide-reaching potential, allowing for comprehensive studies of charm (D^0 , D^+ and

¹ The development of high luminosity machines is also clearly beneficial for the health of accelerator-based physics, as discussed in the EPS-ECFA joint session at EPS2007.

Table 1. Expected precision of some of the most important measurements that can be performed at SuperB with 75 ab^{-1} . Numbers quoted as percentages are relative precisions. Values given for rare tau decays are the 90% confidence level upper limits expected in the absence of signal. Measurements marked (†) will be systematics limited; those marked (*) will be theoretically limited. In many of these cases, there exist data driven methods of reducing the errors.

Observable	Precision	Observable	Precision
$\sin(2\beta)$ ($J/\psi K^0$)	0.005 (†)	$\mathcal{B}(B \rightarrow \tau \nu)$	4% (†)
α ($\pi\pi, \rho\pi, \rho\rho$ combined)	1–2° (*)	$\mathcal{B}(B \rightarrow \mu \nu)$	5%
γ ($B \rightarrow DK$, combined)	1–2°	$\mathcal{B}(B \rightarrow D\tau \nu)$	2%
$ V_{ub} $ (inclusive)	2.0% (*)	$\mathcal{B}(B \rightarrow \rho \gamma)$	3% (†)
$S(\phi K^0)$	0.02 (*)	$A_{CP}(b \rightarrow s \gamma)$	0.004 (†)
$S(\eta' K^0)$	0.01 (*)	$A_{CP}(b \rightarrow (s + d) \gamma)$	0.006 (†)
$S(K_S^0 K_S^0 K_S^0)$	0.02 (*)	$S(K_S^0 \pi^0 \gamma)$	0.02 (*)
ϕ_D	1–3°	$S(\rho^0 \gamma)$	0.10
$\mathcal{B}(\tau \rightarrow \mu \gamma)$	2×10^{-9}	$A^{FB}(B \rightarrow X_s \ell \ell) s_0$	5%
$\mathcal{B}(\tau \rightarrow \mu \mu \mu)$	2×10^{-10}	$\mathcal{B}(B \rightarrow K \nu \bar{\nu})$	20%

D_s^+) and beauty (B^+ and B_d^0) mesons as well as tau leptons. This facility is thus established as the foremost priority for flavour physics, yet it must be emphasized that it is complementary to dedicated experiments in the kaon and muon sectors, while observables related to B_s^0 meson oscillations can be better measured elsewhere.

There is insufficient space in this article to describe even a fraction of the most important measurements from the broad physics programme of SuperB [1]. The machine design has several apparent advantages compared to conventional upgrades of the existing B factories [2]. These include: peak instantaneous luminosity in excess of $10^{36} \text{ cm}^2\text{s}^{-1}$, providing for nominal integrated luminosity of 75 ab^{-1} after five years of operation; detector backgrounds and power consumption comparable to the current B factories; flexible centre-of-mass energy and an option for beam polarization that extend the reach for several interesting observables. These points notwithstanding, for the physics at the $\Upsilon(4S)$ there is much in common between the programmes of machines with different designs [3].

Tab. 1 summarizes the sensitivity of SuperB for some of the most important observables. The differences compared to the current B factories are striking. The SM CKM parameters can be precisely measured, even in the presence of arbitrary NP contributions (assuming progress in the precision of lattice QCD calculations [1]), providing the necessary reference point for interpretation of NP signals. At SuperB, measurements of known rare processes such as $b \rightarrow s \gamma$ or CP violation in hadronic $b \rightarrow s$ penguin transitions such as $B^0 \rightarrow \phi K_S^0$ will be advanced to unprecedented precision. Channels which are just being observed in the existing data, such as $B^0 \rightarrow \rho^0 \gamma$, $B^+ \rightarrow \tau^+ \nu_\tau$ and $B \rightarrow D^{(*)} \tau \nu$ will become precision measurements. Furthermore, detailed studies of decay distributions and asymmetries that cannot be performed with the present statistics will significantly improve the sensitivity to NP. A salient example lies in D^0 – \bar{D}^0 oscillations: the current evidence for charm mixing, which cannot be interpreted in terms of NP, opens the door for precise measurements of the CP violating phase in charm mixing (ϕ_D), which is known to be zero in the Standard Model with negligible uncertainty. In addition, these measurements will be accompanied by dramatic discoveries of new modes, including decays such as $B^+ \rightarrow K^+ \nu \bar{\nu}$ and $B^+ \rightarrow \pi^+ \ell^+ \ell^-$, which are the signatures of the theoretically clean quark level processes $b \rightarrow s \nu \bar{\nu}$ and $b \rightarrow d \ell^+ \ell^-$ respectively.

There has been much recent activity exploring the interplay between flavour observables and

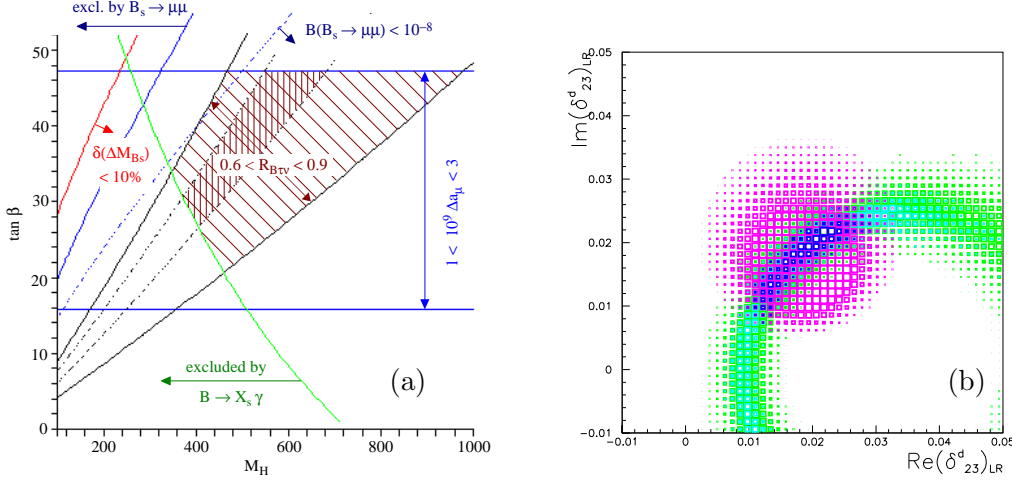


Figure 1. (a) Constraints in the $\tan\beta$ - M_{H^+} plane obtained from Δm_s , $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$, Δa_μ , $\mathcal{B}(B \rightarrow X_s\gamma)$ and $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau)$ [7]. (b) Constraints on the mass insertion parameter $(\delta_{23}^d)_{LR}$ that could be obtained by SuperB, using measurements of $\mathcal{B}(B \rightarrow X_s\gamma)$ (green), $\mathcal{B}(B \rightarrow X_sl^+l^-)$ (cyan), $A_{CP}(B \rightarrow X_s\gamma)$ (magenta) and all combined (blue) [1].

measurements that will be made at the LHC [4]. This work constitutes preliminary steps towards the ultimate challenge of reconstructing the new physics Lagrangian from the combination of experimental inputs. However, one outcome is particularly relevant for today.

Any new-physics model, established at the TeV scale to solve the gauge hierarchy problem, includes new flavoured particles which may be discovered at the LHC. Since these must couple to the SM particles, the NP cannot be flavour blind, and flavour observables must be affected. Indeed, this is the origin of the “flavour problem” – *i.e.* the nonappearance to date of NP in flavour observables such as neutral meson mixing parameters. A solution to this problem can be found in the concept of minimal flavour violation (MFV), whereby NP follows the SM pattern of flavour- and CP - violation encoded in the CKM quark mixing matrix [5].

Although the MFV scenario is far from established (and could only be verified by precise measurements of flavour observables), it is nonetheless very useful to define the minimum NP-sensitivity of flavour. It has been shown that even in such an unfavourable case, SuperB can still detect deviations from the SM for NP particle masses up to at least 600 GeV [1]. At large values of $\tan\beta$ (the ratio of Higgs vacuum expectation values), this bound is raised by at least a factor of three. A good example of this is shown in Fig. 1(a), where the constraints from various flavour observables in the $\tan\beta$ - M_{H^+} plane are shown in a MFV scenario, which could be realised in a two Higgs doublet model or in the MSSM [6, 7]. Once other possible extensions to MFV are considered, the phenomenology accessed by SuperB rapidly becomes much richer, allowing NP flavour couplings that are not accessible at LHC to be measured. An example is shown in Fig. 1(b), where one of the MSSM mass insertion parameters can be completely determined from SuperB measurements [1]. Similar conclusions hold for all NP parameters related to $b \rightarrow s$ or $b \rightarrow d$ transitions.

On the other hand, it is entirely possible that the masses of new particles may be out of reach of the LHC. In this case, SuperB can be used to probe much higher mass scales, since NP models with unsuppressed flavour couplings can cause visible effects even if the new particles have masses of $\mathcal{O}(100 \text{ TeV})$ or more. Thus, SuperB can provide essential complementary information on NP, regardless of whether or not it is discovered by LHC.

It is important to emphasise that SuperB is not limited to the study of B mesons, but

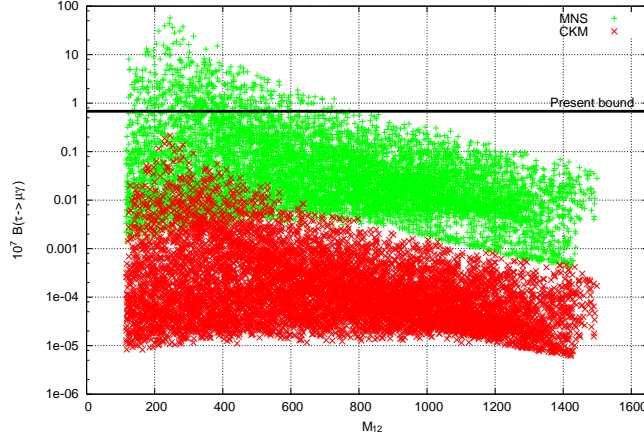


Figure 2. $\mathcal{B}(\tau \rightarrow \mu\gamma)$ in units of 10^{-7} vs. the high energy universal gaugino mass ($M_{1/2}$) within a $SO(10)$ framework [9]. Green and red points correspond to the scenarios where $Y_\nu = U_{\text{PMNS}}$ and where $Y_\nu = V_{\text{CKM}}$, respectively. The thick horizontal line denotes the present experimental sensitivity, which would be improved by almost two orders of magnitude at SuperB.

is really a Super Flavour Factory. In particular, searches for lepton flavour violating (LFV) tau decays provide an interesting link with neutrino oscillations. In models with Majorana neutrinos, LFV processes occur at rates that depend on the heavy masses. Moreover, the pattern of neutrino mixing angles suggests that $\tau \rightarrow \mu\gamma$ decay should have the largest LFV rate, while that for $\mu \rightarrow e\gamma$ may depend on the as-yet-unmeasured value of θ_{13} [8]. Furthermore, one of the most interesting possibilities in NP models is the unification of quark and lepton sectors. As an example, Fig. 2 shows the prediction for $\mathcal{B}(\tau \rightarrow \mu\gamma)$ within a supersymmetric $SO(10)$ framework [9]. as a function of the gaugino mass $M_{1/2}$. The scenarios where the source of LFV violation is governed by neutrino mass matrix $Y_\nu = U_{\text{PMNS}}$ and where $Y_\nu = V_{\text{CKM}}$ can be distinguished. SuperB has sensitivity for tau physics that is superior to any other existing or proposed experiment, even in channels that appear well-suited to the LHC, such as $\tau \rightarrow \mu\mu\mu$.

To summarize, the case for flavour physics in the LHC era is compelling. A Super Flavour Factory is the ideal tool to cover as much as possible of the wide range of interesting physics in both quark and lepton sectors. Many more details on the physics case can be found in the conceptual design report for SuperB [1].

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